DUNLAP & MUNCH

An Investigation of Electric Welding

Electrical Engineering

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AN INVESTIGATION OF ELECTRIC WELDING

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Andrew Melvin Dunlap and Arthur Hiram Munch

ENTITLED An Investigation of Electric Welding

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

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INTRODUCTION.

The following pages contain the results of an investigation of the methods of electric welding, including a short history of the invention and perfecting of the process. A description of some of the machines used in the practical application of the process to present day manufacturing, and actual tests made by the writers of this thesis on a number of small specimens.

The machine used was designed to weld small specimens by the resistance method. Herein is also shown the data obtained from the tests, together with the results obtained from the series of readings as well as from the results in general obtained at various times from other experiments, and from the actual use of the process by manufacturers in their shops.

HISTORY OF ELECTRIC WELDING.

Since the discovery of the electric current many important and useful inventions have been made, which utilize this wonderful agent in the production and manufacture of various commodities.

The adaptability of this same agent to the welding of metals, was, however, absolutely unknown to the world until Prof. Elihu Thompson obtained patents dated Aug. 10, 1886, which may be regarded as the foundation of the new art.

The earlier use of the process was but little more than an experiment, yet it showed as a result that the new method was entirely practicable and efficient both as to cost and strength of weld.

Previous to the discovery of this method iron and steel were almost the only metals that could be welded, but the writer of an article on electric welding in the Engineering News of May 5, 1888 states that the process has been used successfully on all kinds of metals and their alloys, butween metals of like kinds, and between those of a different structure and composition, as steel and copper, or lead and brass.

The process has been growing in favor from year to year, and new ways for its use in the manufacturing industires are constantly being discovered. Its cleanliness, rapidity, economy, efficiency and ease of control has recommended it wherever its use is possible.

METHODS OF WELDING.

The methods by which the results are obtained are perfectly simple and are two in number, namely, the resistance method

and the arc method.

RESISTANCE METHOD.

It has long been known that the electric current has a heating effect upon a conductor when passed thru it, the amount of heating depending upon the resistance the conductor offers to the flow of current and the amount of current flowing. The amount of this resistance depending upon the size, length and material of the conductor. The relation of the heating effect to the resistance of the conductor and the current in the conductor is given by the expression,

$$\text{Heating} = I^2R$$

Where I is the strength of the current in amperes and R the value of the resistance in ohms. The amount of heat is measured in Bt.U. or more roughly by the rise in temperature. From the preceeding equation we see that I must vary inversely with R, that is, when welding material having a small resistance the value of I must be increased.

Iron having a comparatively low resistance will require a correspondingly larger current to produce a welding heat. The resistance of a conductor decreases with increase of cross-section, so more current must be used for large stock than for smaller stock of the same material and vice-versa. The resistance of the stock alone does not produce a welding heat but the reduced area in actual contact between the pieces to be welded, together with the impurities at that point, such as rust, scale, dirt etc. increases the resistance very materially, so much so, in fact that this increased resistance is the main factor in localizing the heat, one of the most important advantages of the process.

The current used in the resistance method may be obtained direct from a direct current generator, or from an alternating current generator, afterwards passing it thru a step-down transformer.

In the first case the current is generated at the desired voltage and used directly on the welding machine. In the second case it is generated at a high voltage and low current then changed in the transformer to the desired voltage and current value. The second arrangement is usually the more practicable and convenient since the power for welding may be used at greater distances from the generator. The first method requires a heavy copper conductor to carry the large current, which prohibits the welding operation from being carried on at any great distance from the direct current generator. The welding transformer in the simplest form consists of a soft iron core around which is wound the primary winding consisting of many turns of small insulated wire, over this is would a few turns of heavy insulated copper cable which compose the secondary coil. The terminals of this secondary coil are then firmly attached to clamps which hold the pieces to be welded. The generator current may have a potential, from 110 volts up to the high pressures of the power circuits 2300 volts and higher. This voltage is transformed or converted, according to the ratio of transformation to enormous current values sometimes as high as 40000 amperes, as in the case of rail welding, the pressure however being very low, from 2 to 4 volts.

The pieces to be welded are clamped solidly in the special terminals of the secondary coil, the surfaces to be welded are then brought together and held with a high pressure while

welding, the switch is closed and a few seconds suffice to produce a perfect weld. The amount of current is exactly regulated by a resistance in the primary circuit or in some instances in the field of the generator where the whole power output of the generator is used in the welding.

On passing the current thru the pieces to be welded the heat at the point of contact rises rapidly until condition of fusion is reached in both pieces, at which point the current is turned off, the metal running together and forming a perfect union. The heating is uniform since if any certain part becomes hotter than the remainder that part has a greater resistance than the cooler portion and so receives less current and therefore less heat until the temperature becomes uniform over the whole area.

ARC METHOD.

The second method of welding by means of the electric current makes use of the electric arc, which has a temperature of an extremely high value ranging from 3000 to 4000 degrees centigrade. There are several different methods in arc welding, the two most important being the Zerener and Bernardos methods. The Zerener or blow pipe method makes use of the arc maintained between two carbons, being directed against the metals to be welded by the action of an electromagnet. The apparatus employed is much like direct current flaming arc lamps the carbons approaching each other at an angle. The electromagnet produces an effect upon the arc similar to that of a blow torch the arc flame being directed away from the carbon points in a concentrated pencil like form and having a high temperature. The work to be welded is so placed

that the arc may be directed against it. The general construction of the apparatus is such that it is useful within only a narrow range, such as small castings and other small work of a rougher nature.

In the Bernardos arc welding process the work to be welded forms one terminal of the direct current circuit and a carbon electrode the other. With the switch closed the carbon is touched to the work and then drawn a short distance away until an arc is formed between the terminals. This arc has such a high temperature that metals may be entirely melted away, cut in two, or fused into one piece. The circuit for control of the current which ranges from 400 to 1000 amperes must be so arranged as to give a variable resistance and one method is as shown in the following diagram.

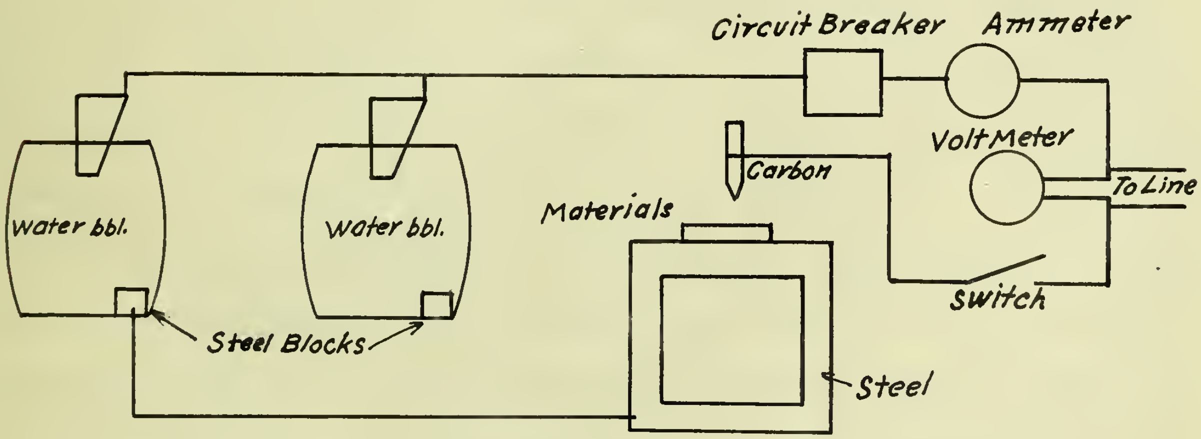


Figure 1.

Diagram Showing Method of Current Control, in the Bernardos Arc Welding Process.

Girds may be used in place of the water resistances, lugs being provided at different points for the attachment of the wires in order that the resistance in the circuit may be varied. The carbon varies in size according to the size of the work to be done and is from one half to two inches in diameter. The heat and light given off by this process is so intense that the operator must be thoroughly protected leaving no part of the body exposed as an inflamation similar to a sunburn may be produced. The work being entirely done by hand requires a skilled operator. This arc is used for removing extra metal, for cutting thru bars, for filling in and for building on metal to castings. It was employed in the destruction of the Ferris Wheel on the grounds of the World's Fair at St. Louis.

USE OF ELECTRIC WELDING IN MANUFACTURING.

As has previously been stated, the simplicity of the process makes its use possible in an ever increasing number of industries. Its chief use at present is found in the welding of small machine parts, the manufacturing of wire fencing, the making of shells and tubing, and the bonding and welding of the rails of city and interurban railways. Carriage and buggy axles, and tires of all sizes are electrically welded, the only limit to the size of material being the value of current that may be produced, however practical use of the process has not been attempted on stock over 2 in. in diameter or on rectangular pieces over 4 sq. inches in sectional area. A very useful application of the process is in repairing broken machine parts which otherwise would require a new piece. Much use has been found for it in the manufacture of automobiles and bicycles, while several large plants use it in the

production of steel tubing of all sizes up to sixteen inches in diameter. With the increased use of the process there has been a wonderful development of welding machines. The simplest type is operated by hand and consists of two clamps which receive the current and hold the material with a lever or screw for producing the pressure. Welding machines are now built that operate automatically and continue in operation so long as power and material is supplied. Chain welding and wire fence welding machines are excellent illustrations of automatic machines. It has been found that automatic machines will produce more perfect welds than the most skillful hand operators wherever they can be used.

There are three types of welds that are made by this process, the butt weld, the lap weld, and the spot weld. In making a butt weld a burr or fin is produced which must be removed. The lap weld is familiar to all and can be produced in a perfect form. The spot weld is peculiar in that only a small part of the surfaces in contact are welded. This weld is used in joining sheets or plates of steel or iron of less than one quarter inch each in thickness.

In operation the electrodes or secondary terminals are placed opposite each other with the metal plates between them, pressure is applied and the current turned on. In a few seconds the sheets are welded in a spot as large as the electrodes. By welding several points in this manner the sheets are firmly fastened togehter.

For the welding of rails special apparatus of a heavy and costly nature is necessary. The outfit consists of three cars, one containing a booster set, one a rotary converter, and one a

welding transformer. The transformer is swung from a heavy beam projecting in front of the car and so mounted as to allow it to be moved from side to side and raised or lowered at will. The secondary circuit of the transformer constitute the jaws of the clamp and are made hollow to provide for water cooling.

ADVANTAGES OF ELECTRIC WELDING.

The chief advantages of the process of welding metals by the use of the electric current may be briefly enumerated as follows:

1. It is simple in operation, requiring little skill on the part of the operator, hence eliminating the expense of skilled labor.

2. The operation is almost instantaneous, thus the work of welding may be carried on successfully with great rapidity.

3. The operator has perfect control over the process and can vary the current, pressure and time of operation to suit the work in hand.

4. Correct alignment of the parts welded is assured since the machine clamps rigidly hold the parts in the desired position, during the operation.

5. The weld is made in full view of the operator, enabling him to closely observe each part of the process.

6. In making the weld, the interior of the joint receives the heat before the exterior, hence there is greater possibility for a perfect weld than with the process of heating the metal in a coal or gas fire where the exterior is the first part heated.

7. The heat is localized at the weld, no other parts being effected, therefore little danger of injuring the composition

or destroying the finish on parts adjacent to the weld itself.

8. The process is free from danger of any kind of shock to the operator, for altho a very large amount of current is necessary to produce the welding heat, the potential which forces it thru the joint is very low.

9. The pressure applied by the operator during the process forces the slag and scale out of the weld, driving out many of the impurities from the metal.

10. The economy of this method compared with others is clearly evident since all the energy applied is utilized in producing the weld, none is wasted when the welding is not in process.

11. This method has made possible successful welding of such metals as copper, brass, aluminum which heretofore have been difficult to weld by other processes.

12. There is a distinct absence of noise, dirt, smoke, intense heat, and dangerous gases, so often present when welding metals by other processes.

DESCRIPTION OF APPARATUS USED.

All the welds made in this investigation were made by the resistance method upon a simple machine designed and constructed by James William Shaw as part of a thesis on Methods of Welding Metals, for the degree of Bachelor of Science at the University of Illinois.

The machine consists of two cast iron jaws mounted upon a lathe bed, the jaw A being in two parts, the upper part being a heavy brass plate insulated by fiber board from the heavy cast iron base which is clamped to the lathe bed.

The jaw B is in three parts, consisting of a heavy cast

iron base clamped to the frame, this piece carries a sliding block of cast iron, the two being dovetailed together, to this second piece is attached the toggle joint connecting with the hand pressure lever by means of which a heavy pressure is brought to bear upon the specimens to be welded. Upon this sliding piece but insulated from it by fiber board is a second large brass plate. To these plates are secured the terminals of the secondary coil. Groves are cut into these plates to receive the specimens to be welded. Clamps and bolts for holding the specimens are fixed in these copper plates. In setting the specimens in the jaws the possible pressure may be regulated as desired by placing the specimens in the jaws so that when they are in contact the toggle joint is in more or less of a straight line.

The transformer was also designed and built by Mr. Shaw. It is of the shell type, having 168 turns of number 14 double cotton covered magnet wire for the primary coil, and three turns of number 0000 insulated cable for the secondary coil, and is immersed in transformer oil in a case to prevent overheating.

The core loss of the transformer with 110 volts and 60 cycles on the primary is 23.5 watts, magnetizing current .47 amperes. Using 220 volts on the primary the core loss is 71.5 watts, and the magnetizing current .97 amperes. The resistance of the primary is .787 ohms.

The instruments used were, a Westinginghouse portable integrating wattmeter calibrated to read in watt minutes. This instrument has two sets of voltage terminals, one for 110 and the other for 220 volts. A system of plugs in the current coil makes it possible to use values of current in the primary circuit up to

40 amperes.

The ammeter was of the Thompson type with a range from 0 to 50 amperes. The voltmeter was a Weston instrument with a range from 0 to 300 volts. The diagram of connections is self explanatory, power entering at the double pole switch which connects with the primary of the transformer.

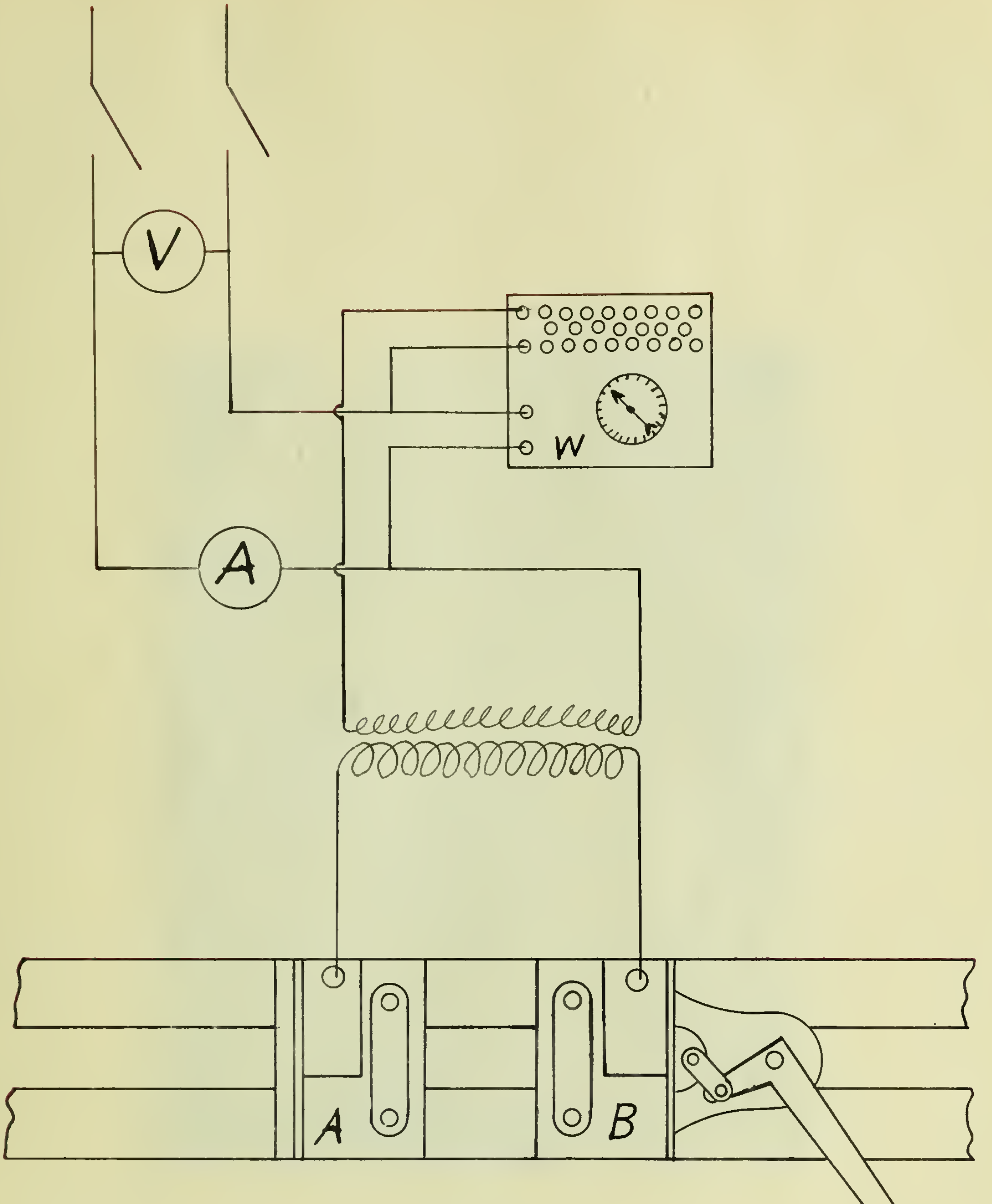


Figure 2.

Diagram of Connections including Welding Transformer and Hand Welding Machine.

METHOD OF MAKING WELDS.

The resistance method was employed exclusively in welding the specimens. Bar iron was obtained and cut into test specimens, six inches in length. One end of each test piece was carefully faced. Two of these pieces were then clamped in line between the jaws of the welding machine, with the faced ends about 1/8 of an inch apart. The switch controlling the flow of current in the primary circuit was then closed and immediately following the specimen pieces were forced together by means of the hand lever. The latter action closed the secondary circuit of the transformer and instantaneously a heavy current flowed thru the test pieces. The pressure exerted on the specimens was increased or decreased as desired, thereby increasing and decreasing the resistance between the pieces and causing a larger or smaller amount of current to flow in the secondary circuit.

When the metal had reached its fusion point, the primary switch was opened and a slightly greater pressure exerted on the specimen in order to force out any burnt metal, slag or scale from the center of the weld.

63 specimens of mild steel in sizes ranging from 3/16" to 1/2 inch were welded. 9 specimens each of wrought iron and machine steel of sizes 3/8 of an inch in diameter and 3/8" x 3/8" respectively were also welded. The average voltage impressed on the primary of the transformer ranged from about 110 and 220 volts for the small stock to about 250 volts on the larger size specimens. It was found that on account of the small size of the welding transformer, that 220 volts on the primary of the same was not sufficient to give the necessary current to weld stock larger than 3/8 of an

inch in diameter, hence higher voltages had to be resorted to.

Too large a value of current will burn the metal before the operator can effect a weld while too small a value of current does not bring the metal up to its fusion point, hence it was found only by experiment, the best value of current for the size of material to be welded. It is hoped however that the following data given in pages 18 to 27 inclusive may be of assistance in serving as a rough guide in future work along this line.

No flux was used on welding any of the specimens and judging from the results obtained in this test it is reasonable to believe that the use of flux would be of no special advantage in this method of welding metal.

TESTING OF THE WELDS.

After welding the specimens, the burr or swelled joint at the weld was turned down to the original diameter of the stock and each specimen tested for ultimate tensile strength, in order to determine the efficiency of the weld. This operation was performed on a Riehle Testing Machine in the Laboratory of Applied Mechanics at the University of Illinois. The ends of the specimen was securely clamped in jaws of the machine and load applied until rupture occurred. The welds which were perfectly annealed withstood the strain and the specimen ruptured at a distance from the weld itself. Other welds in which the metal was less perfectly annealed, containing slag, scale, or burnt metal, broke in the weld itself.

Samples of the stock, from which the welded specimens were made, were also tested for ultimate tensile strength. The efficiency of the weld was then determined by the ratio of the

ultimate tensile strength of the welded specimen to that of the material itself, expressed in percent.

In a number of cases, the ultimate tensile strength of the welded specimen was greater than that of the material, giving the welds a percent efficiency greater than 100.

It was noted that the cold rolled machine steel specimens had a high elastic limit or yield point and that the cross-sectional area of the welded portion was reduced about one-third of its original size just before rupture occurred. This does not refer to the "necking down" of the specimen at point of rupture but to a general elongation of the specimen between the machine jaws.

METHODS OF COMPUTING RESULTS.

The ultimate tensile strength of a specimen is the highest stress that the specimen can sustain before rupturing, when under tension. The efficiency of a welded specimen or the weld is the ratio of the ultimate strength of the specimen to that of the material itself, expressed in percent. For example in Table 1, referring to specimen 2, it is seen that the ultimate tensile strength of the specimen is 1840 lb. and the ultimate tensile strength of the material is 1900 lb. Therefore the effeciency of the weld is $\frac{1840}{1900} \times 100\% = 96.8\%$.

The value of secondary current was obtained by multiplying the value of primary current used by 56 since the ratio of turns on the primary and secondary coils is 56 : 1. The value of magnetizing current was so small in comparison with the primary current, that it was neglected.

In computing the power consumed in producing the welds, the transformer losses were neglected on account of their small

value in comparison to the power used. In figuring the cost of power for each weld it was necessary to charge these losses up to the weld.

The wattmeter used, recorded the power used for producing each weld, in watt hours. This was easily reduced to kilowatt hours by dividing the value obtained from the instrument by 1000.

The cost of power was figured at three commercial rates, two, four, and six cents per kilowatt hour, as shown in the tables on pages 18 to 27.

Tables were made showing the results of welding each size of stock. These show for each specimen, time of welding, average secondary current, average power in kilowatt hours, ultimate tensile strength of each welded specimen and material from which it was made, percent efficiency of weld, cost of producing the weld at three rates of cost, and the primary voltage impressed on the transformer.

Table I.

Mild Steel 3/16 inch Diameter.

No. of Specimen	1	2	3	4	5	6	7	8	BE 9
Time in Seconds	15	12	10	10	10	10	15	10	13
Average current in Secondary amperes	613.5	613.5	684.0	670.0	544.0	583.0	621.0	641.0	600.0
Power in K. W. hours	.0049	.0038	.0037	.0036	.0029	.0031	.0051	.0034	.0043
Ultimate Tensile Strength of Specimen lbs.	1920*	1840*	1910*	1390	1900*	1740	1930*	1400	1900*
Ultimate Tensile Strength of Material lbs.	1900	1900	1900	1900	1900	1900	1900	1900	1900
Efficiency of Weld in per-cent	100+	96.8	100+	73.2	100	91.6	100+	73.7	100
Cost of Weld in Cents at 2, 4, 6 cents per K. W. hr.	.0098 .0196 .0294	.0077 .0154 .0231	.0074 .0149 .0224	.0072 .0144 .0216	.0058 .0116 .0175	.0063 .0127 .0190	.0102 .0204 .0307	.0068 .0136 .0205	.0086 .0172 .0258
Primary Voltage Used volts	107.0	105.5	108.5	108.5	107.0	109.5	110.0	108.5	111.0

*Note. The use of the asterisk indicates that the specimen broke outside of the weld in testing for ultimate tensile strength of welds.

BE. indicates that the specimen peices had beveled ends before being welded.

Table II.

Mild Steel 1/4 inch Diameter.

No. of Specimen	1	2	3	4	5	6	7	8	9
Time in Seconds	15	6	6	30	41.5	41.5	43.5	8	41.5
Average current in Secondary Amperes	1005	1310	1550	684	868	810	863	1390	756
Power in K. W. hours	.0107	.0085	.0100	.0107	.0194	.0181	.0202	.0122	.0173
Ultimate Tensile Strength of Specimen lbs.	2500	1500	1950	3080	3080*	3120*	3130*	3630	3120
Ultimate Tensile Strength of Material lbs.	3230	3230	3230	3230	3230	3230	3230	3230	3230
Effeciency of Weld in per-cent	77.4	46.4	60.3	95.4	95.4	96.6	96.9	100+	96.6
Cost of Weld in Cents at 2, 4, 6, cents per K. W. hr.	.0214 .0428 .0642	.0170 .0340 .0510	.0200 .0400 .0600	.0214 .0428 .0642	.0388 .0776 .1164	.0362 .0724 .1086	.0404 .0808 .1212	.0244 .0488 .0732	.0346 .0692 .1038
Primary Voltage Used Volts	145.5	217.5	217.5	106.0	108.7	108.7	108.5	221.3	111.3

Table III.

Mild Steel 1/4 inch by 1/4 inch.

No. of Specimen	1	2	BE 3	4	5	6	7	8	9
Time in Seconds	7	38	6	21.5	72	26.5	23	28	20.5
Average Current in Secondary Amperes	27.7	15.76	28.63	19.60	13.45	18.60	17.50	18.26	18.80
Power in K. W. hours	.0116	.0239	.0102	.0254	.0284	.0268	.0155	.0193	.0139
Ultimate Tensile Strength of Specimen lbs.	3510	3270	3790	3570*	3000	3630*	3600*	3570*	3950*
Ultimate Tensile Strength of Material lbs.	3840	3840	3840	3840	3840	3840	3840	3840	3840
Efficiency of Weld in per-cent	91.7	85.2	98.8	93.0	78.1	94.5	93.8	93	100+
Cost of Weld in Cents at 2, 4, 6 cents per K. W. hr.	.0232 .0464 .0696	.0478 .0956 .1434	.0204 .0408 .0612	.0508 .1016 .1524	.0568 .1136 .1704	.0736 .1192 .1604	.0310 .0620 .0830	.0386 .0772 .1158	.0278 .0556 .0834
Primary Voltage Used Volts	216	144	213	216.8	105.6	141.5	139.0	136.5	130

Table IV.

Mild Steel 5/16 inch Diameter.

No. of Specimen	1	2	3	BE 4	5	6	7	8	9
Time in Seconds	10	10	10	8.5	32.2	24	37	40	21
Average Current in Secondary Amperes	25.30	28.15	28.25	28.15	19.40	29.15	19.60	18.60	23.65
Power in K. W. hours	.0152	.0170	.0173	.0145	.0235	.0264	.0271	.0291	.0216
Ultimate Tensile Strength of Specimen lbs.	4570	4760	3730	4000	2740	3460	3870*	4450*	3860
Ultimate Tensile Strength of Material lbs.	4685	4685	4685	4685	4685	4685	4685	4685	4685
Efficiency of Weld in per-cent	97.7	100+	79.6	85.3	58.4	73.8	82.6	95.0	82.4
Cost of Weld in Cents at 2, 4, 6 cents per K. W. hr.	.0304 .0608 .0912	.0340 .0680 .1020	.0346 .0692 .1038	.0290 .0580 .0870	.0470 .0930 .1410	.0528 .1056 .1584	.0540 .1084 .1626	.0582 .1164 .1746	.0432 .0864 .1296
Primary Voltage Used Volts	217	218.5	220	218	136.5	135.7	135	140.9	157

Table V.

Wrought Iron 3/8" Diameter.

No. of Specimen	1	2	3	4	BE 5	6	7	8	9
Time in Seconds	23.5	19	17.5	20	16.5	16	21	17	16
Average Current in Secondary Amperes	1547	1784	1995	1670	1603	1905	1625	1653	1778
Power in K. W. hours	.0382	.0357	.0386	.0415	.0319	.0321	.0367	.0298	.0334
Ultimate Tensile Strength of Specimen lbs.	3900	3360	3480	3800	4975	3980	3900	3650	4370
Ultimate Tensile Strength of Material lbs.	5070	5070	5070	5070	5070	5070	5070	5070	5070
Efficiency of Weld in percent	76.8	66.3	68.6	74.8	98.1	78.5	77.8	70.0	86.3
Cost of Weld in Cents at 2, 4, 6 cents per K. W. hr.	.0764 .1528 .2292	.0704 .1428 .2142	.0772 .1544 .1716	.0815 .1660 .2490	.0638 .1276 .1914	.0642 .1284 .1926	.0734 .1468 .2202	.0596 .1192 .1788	.0668 .1336 .2004
Primary Voltage Used Volts	211	215.3	217	215.5	209.5	212	217.5	214	237

Table VI.

Machine Steel 3/8" by 3/8" (Cold Rolled)

No. of Specimen	1	2	3	4	BE 5	6	7	8	9
Time in Seconds	15	18	22	21	17	19.5	22.5	24	20
Average Current in Secondary Amperes	2117	2106	1893	1980	2023	1953	1875	1905	1932
Power in K. W. hours	.0378	.0413	.0430	.0445	.0372	.0442	.0506	.0490	.0420
Ultimate Tensile Strength of Specimen lbs.	6250	6680	8370	6930	8960	7370	6220	10310	10100
Ultimate Tensile Strength of Material lbs.	14425	14425	14425	14425	14425	14425	14425	14425	14425
Efficiency of Weld in per-cent	43.3	46.3	58.0	48.0	62.1	51.1	43.1	71.5	70.1
Cost of Weld in Cents at 2, 4, 6 cents per K. W. hr.	.0756 .1512 .2268	.0826 .1652 .2478	.0860 .1720 .2580	.0890 .1780 .2670	.0744 .1488 .2232	.0884 .1768 .2652	.1012 .2024 .3036	.0980 .1960 .2940	.0840 .1260 .2520
Primary Voltage Used Volts	240	219.8	213	214.2	214.3	234	240	216	219

Table VII.

Mild Steel 7/16" Diameter.

No. of Specimen	1	2	3	BE 4	5	6	7	8	BE 9
Time in Seconds	25	25	35	23	23	25	21.5	23.5	20.5
Average Current in Secondary Amperes	1932	1950	1905	1867	1948	1952	2000	1950	1867
Power in K. W. hours	.0495	.0496	.0670	.0427	.0478	.0600	.0513	.0546	.0448
Ultimate Tensile Strength of Specimen lbs.	7340	8730	9030*	7840	8690	8720	8580	7900	9010
Ultimate Tensile Strength of Material lbs.	9225	9225	9225	9225	9225	9225	9225	9225	9225
Efficiency of Weld in per-cent	79.6	94.7	97.8	85.0	94.3	94.6	93.1	85.7	97.7
Cost of Weld in Cents at 2, 4, 6 Cents per K. W. hr.	.0990 .1980 .2970	.0992 .1984 .2976	.1340 .2680 .4020	.0894 .1708 .2562	.0956 .1912 .2868	.1200 .2400 .3600	.1026 .2052 .3078	.1092 .2184 .3276	.0896 .1792 .2688
Primary Voltage Used Volts	206.7	205	202.4	204.0	215.7	240.0	240.0	240.0	240.0

Table VIII.

Mild Steel 7/16" by 7/16"

No. of Specimen	1	2	3	4	5	6	BE 7	BE 8	9
Time in Seconds	30	36	36	25.5	35.5	29	28	28	30
Average Current in Secondary Amperes	2298	2033	2261	2360	2170	2275	2178	2232	2198
Power in K. W. hours	.0861	.0907	.1068	.0780	.0990	.0875	.0803	.0827	.0884
Ultimate Tensile Strength of Specimen lbs.	10460	10150	* 13220	9800	11240	12400	10860	11500	10880
Ultimate Tensile Strength of Material lbs.	13255	13255	13255	13255	13255	13255	13255	13255	13255
Efficiency of Weld in per-cent	78.9	76.6	99.9	73.9	84.9	93.6	81.9	86.8	82.1
Cost of Weld in Cents at 2, 4, 6 cents per K. W. hr.	.1722 .3444 .5166	.1814 .3628 .5442	.2136 .4272 .6408	.1560 .3120 .4680	.1980 .3960 .5940	.1750 .3500 .5250	.1606 .3212 .4818	.1654 .3308 .4962	.1768 .3536 .5304
Primary Voltage Used Volts	252	247.8	265.8	261.6	259.8	267.0	265.8	267.6	270.0

Table IX.

Mild Steel 1/2" Diameter.

No. of Specimen	1	2	3	4	5	6	BE 7	BE 8	9
Time in Seconds	25	33	45	18	27	30	28	26	29
Average Current in Secondary Amperes	2660	2352	2328	2703	2473	2315	2024	2182	2370
Power in K. W. hours	.0843	.0950	.1220	.0688	.0875	.0918	.0776	.0754	.0885
Ultimate Tensile Strength of Specimen lbs.	6330	9720*	9610*	9800	9750*	9730*	9690*	9800*	13070*
Ultimate Tensile Strength of Material lbs.	9890	9890	9890	9890	9890	9890	9890	9890	9890
Efficiency of Weld in per-cent	63.0	98.3	97.2	99.1	98.6	98.4	97.8	99.1	100+
Cost of Weld in Cents at 2, 4, 6 Cents per K. W. hr.	.1686 .3372 .5058	.1900 .3800 .5700	.2440 .4880 .7320	.1376 .2752 .4128	.1750 .3500 .5250	.1836 .3672 .5508	.1552 .2328 .4656	.1508 .3016 .4520	.1760 .3540 .5310
Primary Voltage Used Volts	255	246.6	236.6	285.0	264.0	267.6	276.0	267.0	260.0

Table X.

Data from which curves are plotted.

Kind of Specimen	Cross-section area in sq. in.	Average secondary current amperes.	Average Power in K.W. hours.	Average Ultimate Strength of Specimen in lbs.	Average Efficiency in per-cent.	Cost of Power at 2¢ per K.W. hr.	4¢ per K.W. hr.	6¢ per K.W. hr.
Mild Steel 3/16" diameter	.0276	618.8	.0038	1770	92.8	.007	.015	.022
Mild Steel 1/4" by 1/4"	.0625	1115.6	.0194	3543	92.1	.042	.079	.115
Mild Steel 1/4" diameter	.0492	1026.2	.0141	2790	85.0	.028	.056	.084
Mild Steel 5/16" diameter	.0768	1399.8	.0202	3938	83.9	.042	.085	.127
Wrought Iron 3/8" diameter	.1105	1724.4	.0353	3935	77.5	.068	.142	.205
Machine Steel 3/8" by 3/8"	.1405	1976.0	.0433	7910	55.0	.075	.168	.259
Mild Steel 7/16" diameter	.1520	1930.1	.0519	8427	91.4	.104	.207	.311
Mild Steel 7/16" by 7/16"	.1912	2222.7	.0999	11168	84.3	.178	.355	.533
Mild Steel 1/2" diameter	.1965	2378.5	.0879	9722	94.6	.175	.342	.527

CURVES.

The curves as shown on Plates 1 to 6 inclusive are designed to show the relation between size of specimen and the following; current input, power consumed, cost of producing the weld, average ultimate tensile strength, efficiency of the weld and percent of specimens of each size stock which ruptured in the weld when tested for ultimate tensile strength.

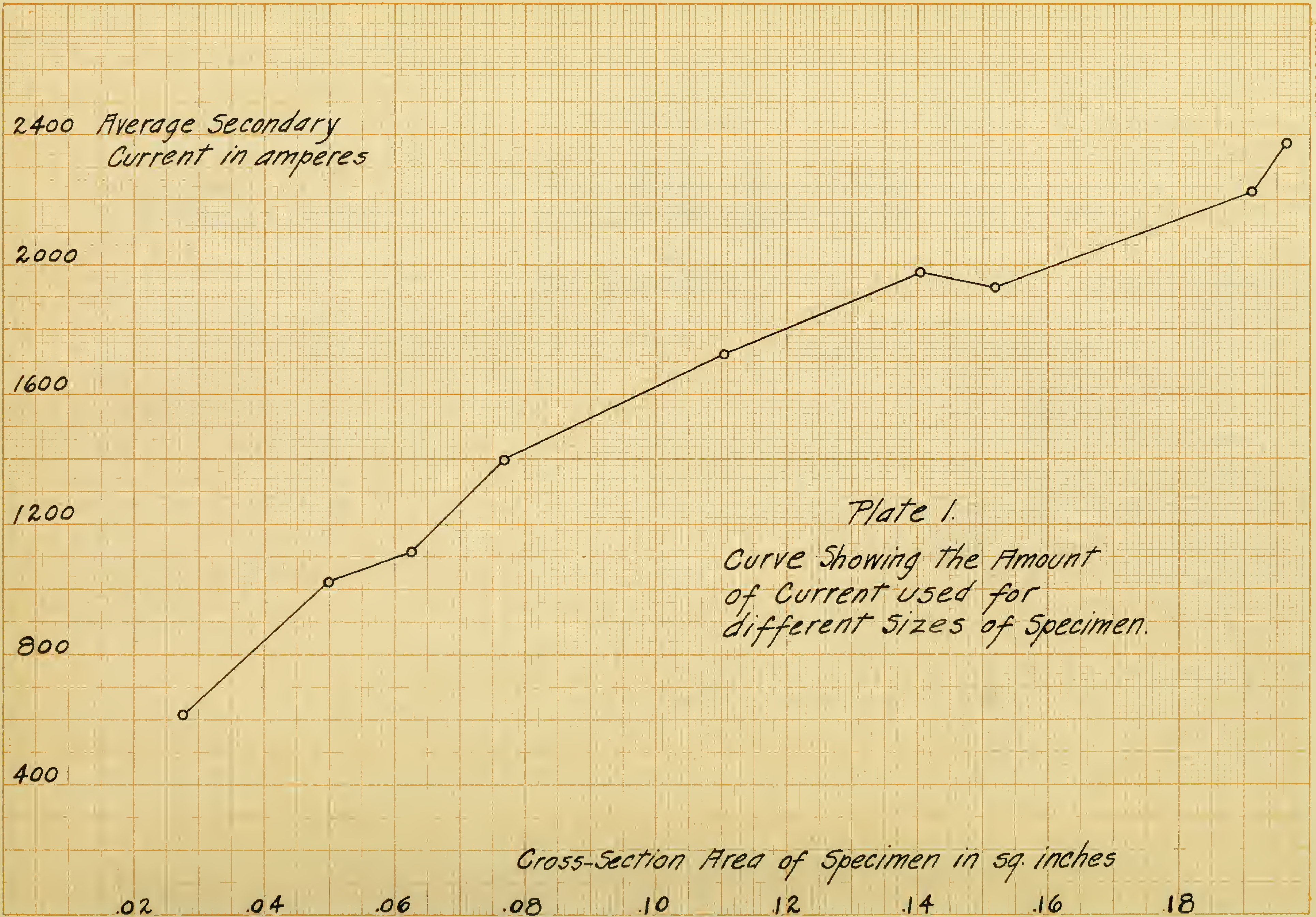
Plate 1 shows a curve, giving an idea of the amount of current actually used in welding the different sizes of specimens.

Plate 2 gives a curve showing the variation of power consumed in making welds with different sizes of stock.

The curves on Plates 3 and 4 are designed to show the average percent efficiencies obtained from the welds of different sizes of specimens. The curves of ultimate tensile strength of material and welded specimens on Plate 3 give an idea of the range of the percent efficiencies plotted on Plate 4.

The graphs of relative cost of welding different sizes of stock on Plate 5 are worked out for power costing two, four, and six cents per kilowatt hour.

The curve on Plate 6 is designed to show the percent of the number of specimens of each size stock which when tested for ultimate tensile strength ruptured outside of the weld proper.


2400 Average Secondary
Current in amperes
2000
1600
1200
800
400
Plate I.
Curve Showing the Amount
of Current used for
different Sizes of Specimen.
Cross-Section Area of Specimen in sq. inches
.02
.04
.06
.08
.10
.12
.14
.16
18
U. OF I. S. S. FORM 3

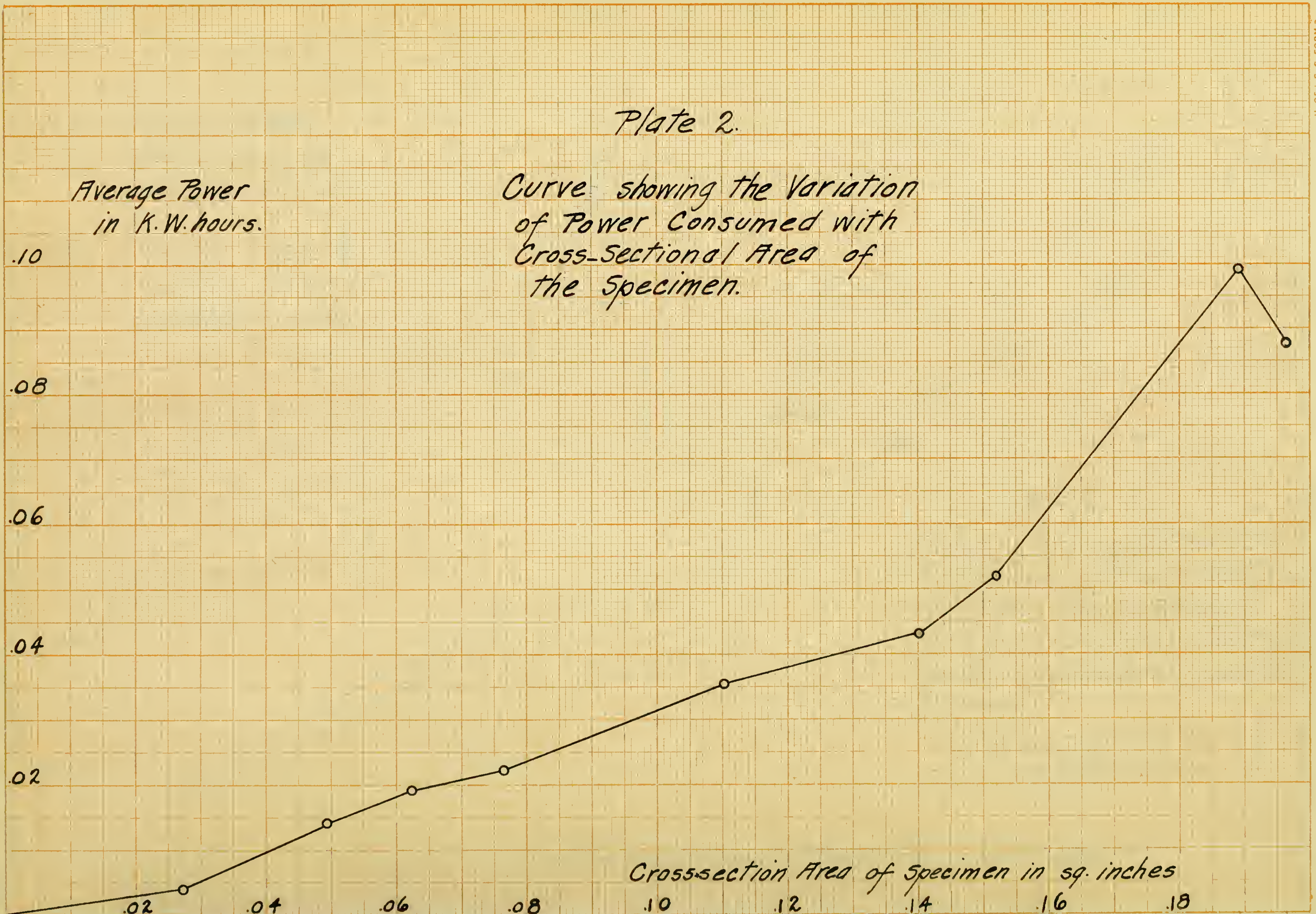


Plate 2.
Curve showing the Variation of Power Consumed with Cross-Sectional Area of the Specimen.
Average Power in K.W. hours.
.10
.08
.06
.04
.02
Crosssection Area of Specimen in sq. inches
.02
.04
.06
.08
.10
.12
.14
.16
.18

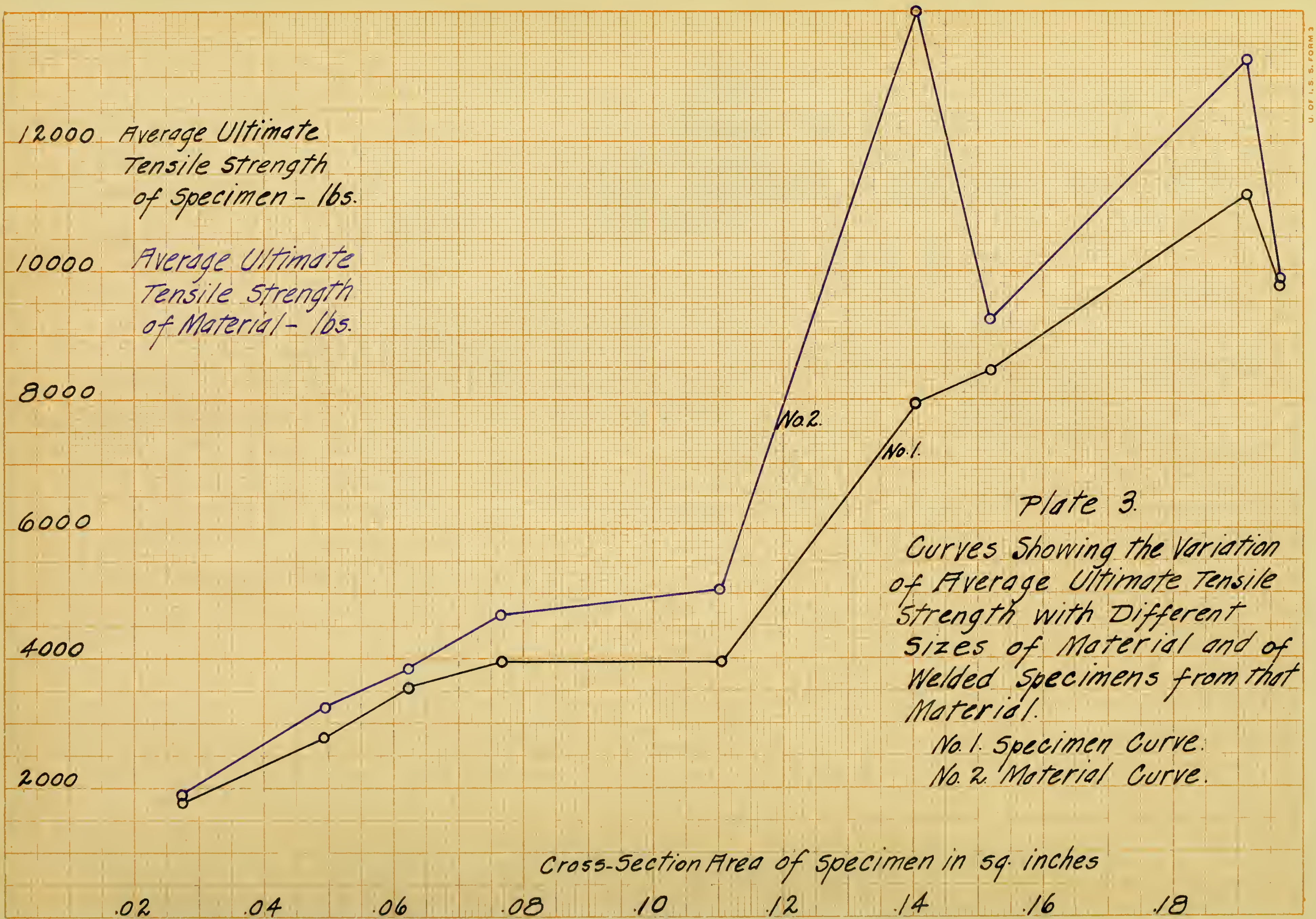


Plate 3.

Curves Showing the Variation of Average Ultimate Tensile Strength with Different Sizes of Material and of Welded Specimens from that Material.

No. 1. Specimen Curve.
No. 2. Material Curve.

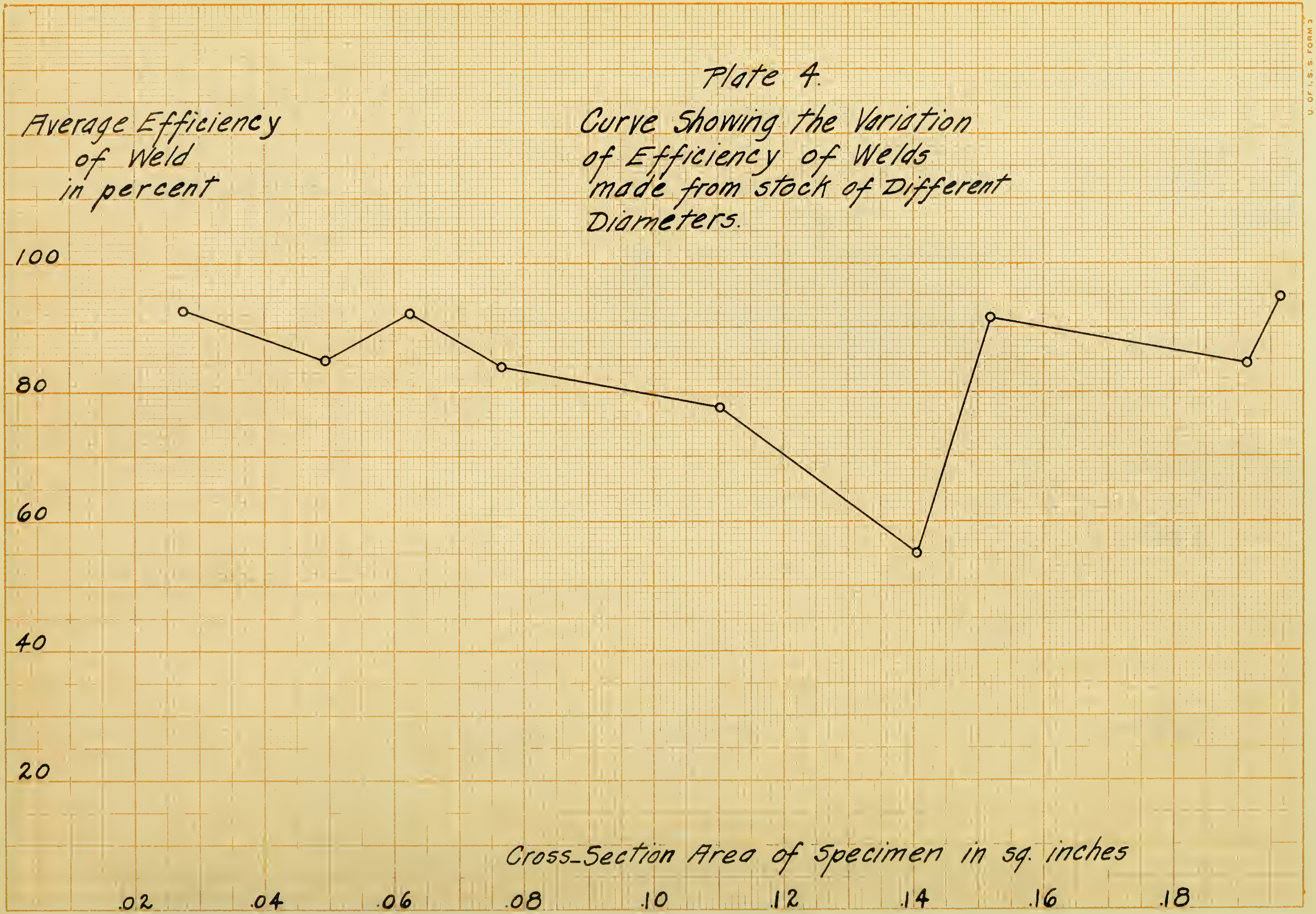


Plate 4.
Curve Showing the Variation of Efficiency of Welds made from stock of Different Diameters.
Average Efficiency of Weld in percent
100
80
60
40
20
Cross-Section Area of Specimen in sq. inches
.02
.04
.06
.08
.10
.12
.14
.16
.18
U. OF I. S. S. FORM 3

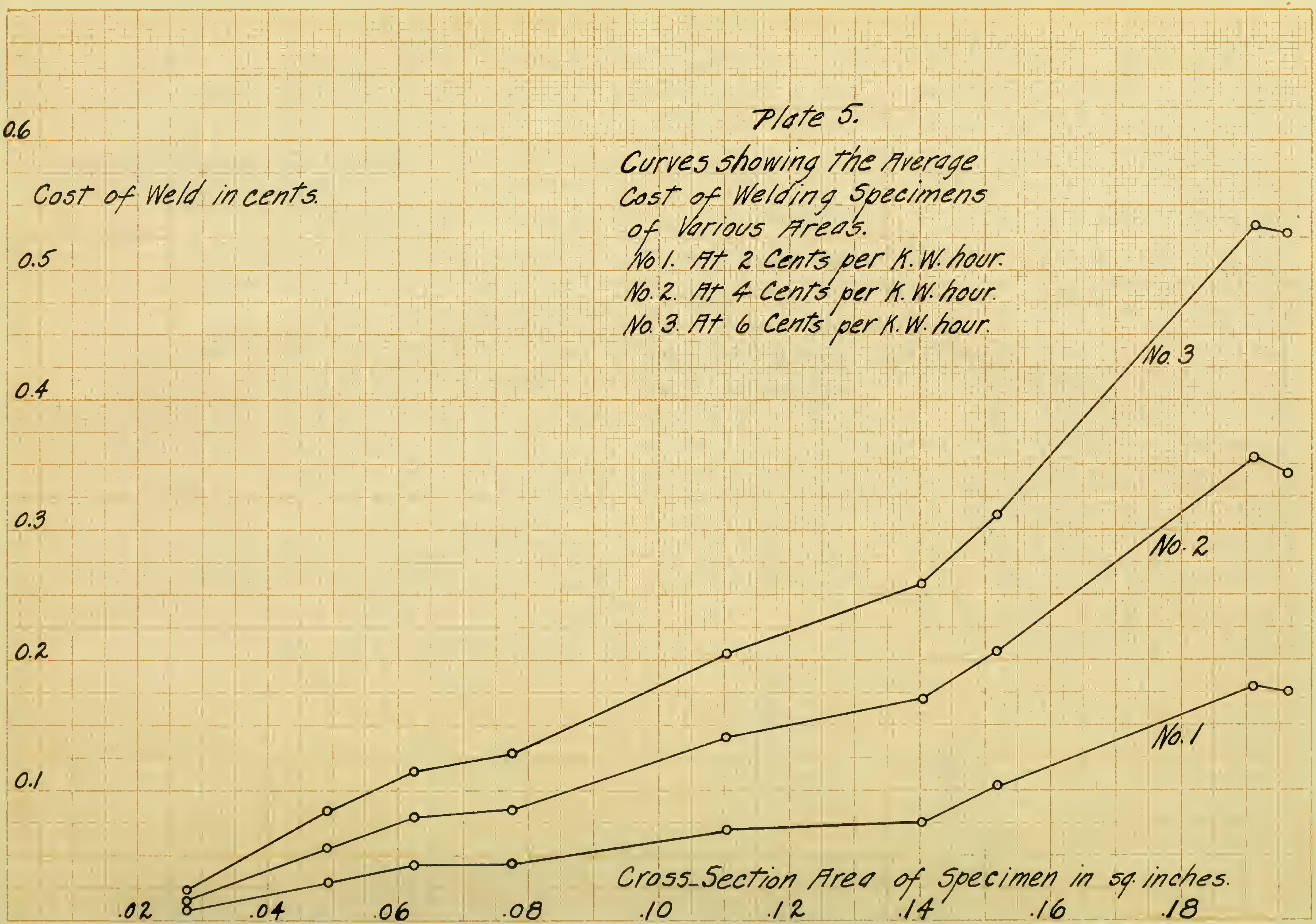


Plate 5.
Curves showing the Average Cost of Welding Specimens of Various Areas.
No 1. At 2 Cents per K.W. hour.
No. 2. At 4 Cents per K.W. hour.
No. 3. At 6 Cents per K.W. hour.
Cost of Weld in cents.
0.6
0.5
0.4
0.3
0.2
0.1
.02
.04
.06
.08
.10
.12
.14
.16
.18
Cross-Section Area of Specimen in sq. inches.
No. 3
No. 2
No. 1

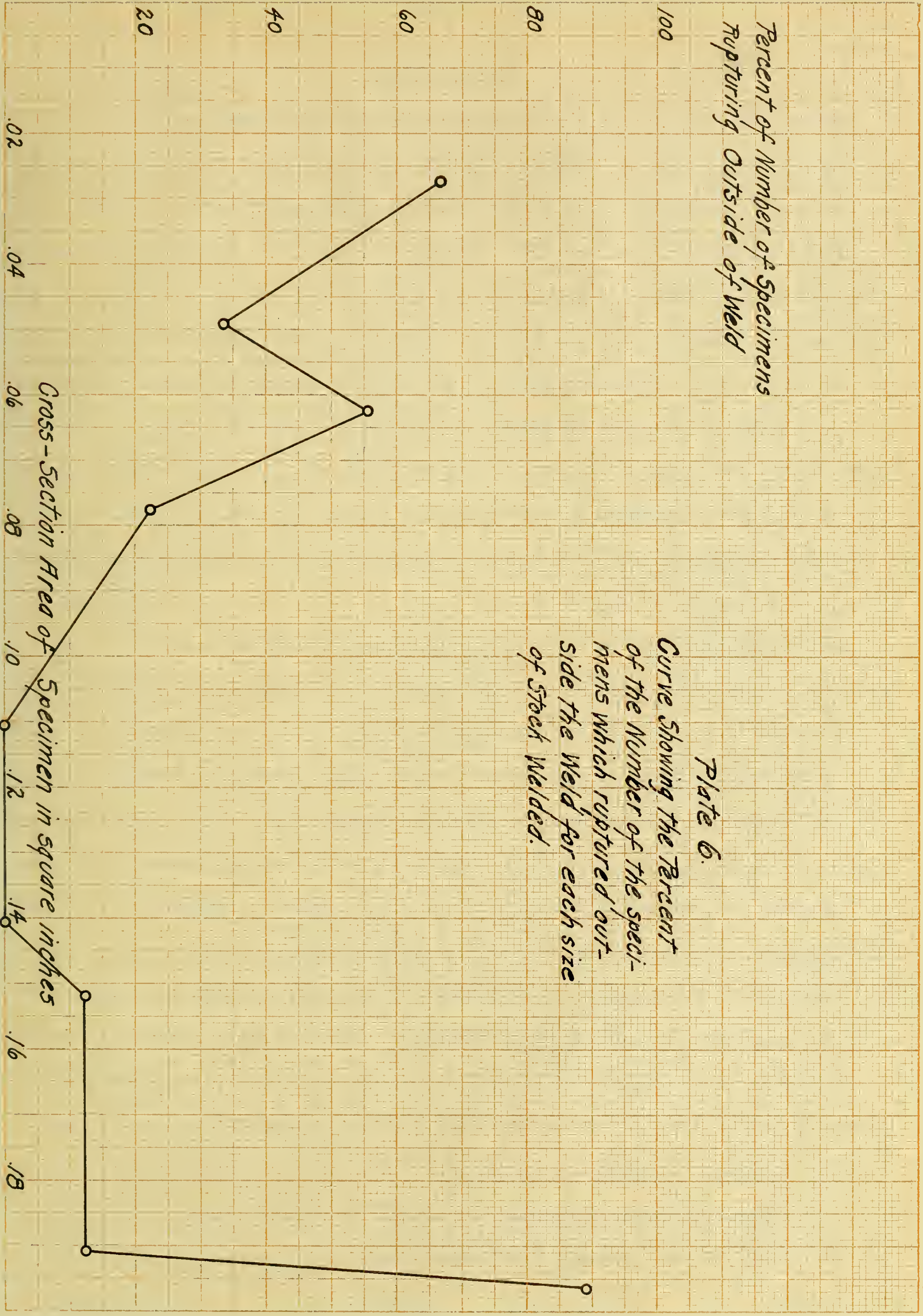


Plate 6.

Curve Showing the Percent of the Number of the specimens which ruptured outside the Weld for each size of Stock Welded.

CONCLUSIONS.

From these tests on welding of metals by the resistance method it may be seen that the proper values of voltage, current and time for obtaining satisfactory welds of different sizes of material cannot be definitely given. The value of voltage used on the primary side of the welding transformer ranged from 102 to 285 volts. Corresponding voltage values on the secondary side of the transformer were 1.8 to 5.1 volts respectively. The lowest value of secondary current used for welding was 613.5 amperes, used on 3/16 inch stock, the highest being 2660 amperes, which was used to weld stock 1/2 inch in diameter. The curve on Plate 1 shows the average values of current used to weld the other sizes of specimens.

The average time required in performing the operation varied from 11 seconds on the smallest size specimens to 30 seconds for the larger sizes. It was found that by using a low value of voltage and of current much longer time was required to secure a desirable weld. When high voltage is available, it is better to use it in preference to low voltage. In the case of using a step down transformer in connection with the welding machine, as was used in this test, high voltage in the primary causes a corresponding high current to flow in the secondary circuit of which the test specimens form a part. Using a high value of current, as is consistent with the size of the parts to be welded, for a short time, is to be preferred to a lower value of current for a longer time, since in the first case, the metal is quickly brought to a welding heat and slight pressure is required to effect a good union of the metals, and force out slag, scale, burnt iron, etc.

from the center of the welded portion.

The total number of specimens welded was 81. Of these, 63 were of mild steel and 9 each of wrought iron and machine steel. 11 percent of the total number of welded specimens were found to have a weld efficiency of over 100 percent. 36 percent had an efficiency of over 95 percent, and 48 percent possessed an efficiency greater than 90 percent. 16 percent of the total number gave a percent efficiency less than 70. One third of the welded specimens, when tested for tensile strength broke outside the weld proper.

Difficulty was experienced in obtaining good welds from the cold rolled machine steel. As may be seen by the efficiency curve on Plate 4, the average efficiency for the nine specimens welded, was only 55%. It was noted in the test for tensile strength that this material is highly elastic, possessing a high yield point. Examination of the ruptured specimens brought out the fact that the metal was not well fused to form a perfect union at the weld.

Some difficulty was also experienced in welding of wrought iron. As shown in the Table 5 on page 22 , the best results were obtained in a specimen welded from test pieces having beveled ends. With one exception, this specimen, (No. 5), required less power than the others and gave a high efficiency of 98.1 percent. This clearly shows the advantages of beveling the ends of pieces to be welded. Glancing over the tables from page to page inclusive, it is seen that in the majority of cases, specimens having beveled ends consumed a comparatively small amout of power when welded and gave high percent efficiencies. The reason for this is probably that when welding pieces having beveled ends, the welding process starts at the center and as the pressure is increased, the weld was

made from the center outwards. This action tends to force the slag, scale, and other impurities out of the center of the weld.

The best results were obtained in making welds from the 1/2 inch stock of mild steel. Of the nine welds made from this size stock, eight gave efficiencies of over 97 percent. The average amount of power used in producing these welds was less than that used in welding 7/16 inch by 7/16 inch stock of the same kind of material. It will be noted that a relatively high value of primary voltage was impressed on the welding transformer when welding this size material.

A general examination of all the ruptured specimens brought out the following points:

In every case where the metal at the weld was properly fused, the specimen ruptured at some distance from the weld.

In other cases where the specimen ruptured at the weld, evidences were found of the presence of burnt metal, slag, scale, and other impurities.

Other specimens showed the cross-sectional area of the welded portion considerably reduced, indicating that that portion altho not perfectly welded withstood a heavy strain before rupturing.

As mentioned in "Methods of Testing Welds", the burr or swelled portion around each weld was turned down to the area of the stock before being tested for tensile strength. This action evidently reduced the efficiency of the weld to some extent.